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Smallholder responses to climate anomalies in rural Uganda

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ABSTRACT

Recent research suggests that sub-Saharan Africa will be among the regions most affected by the negative social and biophysical ramifications of climate change. Smallholders are expected to respond to rising temperatures and precipitation anomalies through on-farm management strategies and diversification into off-farm activities. However, few studies have empirically examined the relationship between climate anomalies and rural livelihoods. Our research explores the impact of climate anomalies on farmers' on and off-farm livelihood strategies, considering both annual and decadal climate exposures, the relationship between on and off-farm livelihoods, and the implications of these livelihood strategies for agricultural productivity. To examine these issues, we link gridded climate data to survey data collected in 120 communities from 850 Ugandan households and 2000 agricultural plots in 2003 and 2013. We find that smallholder livelihoods are responsive to climate exposure over both short and long time scales. Droughts decrease agricultural productivity in the short term and reduce individual livelihood diversification in the long term. Smallholders cope with higher temperatures in the short term, but in the long run, farmers struggle to adapt to above-average temperatures, which lower agricultural productivity and reduce opportunities for diversification. On and off-farm livelihood strategies also appear to operate in parallel, rather than by substituting for one another. These observations suggest that new strategies will be necessary if rural smallholders are to successfully adapt to climate change.

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1. Introduction

Over the next century, climate change is expected to have a significant impact on rural livelihoods throughout the developing world (IPCC, 2014). In these regions, people remain largely dependent on agricultural productivity and other natural-resource-based strategies which are vulnerable to rising temperatures and unpredictable rainfall patterns (Iiyama, Kariuki, Kristjanson, Kaitibie, & Maitima, 2008; Knox, Hess, Daccache, & Wheeler, 2012). To adapt successfully to environmental stress, smallholders often employ a range of strategies and responses both in the form of on-farm strategies, such as agricultural intensification, as well as off-farm livelihood diversification into wage labor or small business ownership (Eakin, 2005). Though few studies have considered on and off-farm livelihood diversification simultaneously, previous studies have demonstrated that smallholders shift their agricultural practices as a result of climate stress (Bharwani et al., 2005; Reenberg, 1994; Reenberg, Nielsen, & Rasmussen, 1998; Roncoli, Ingram, & Kirshen, 2001; Thomas, Twyman, Osbahr, & Hewitson, 2007). Likewise, a small number of studies have found that climate stress has influenced smallholder diversification into off-farm livelihoods both as a risk management strategy (Paavola, 2008) and to cope with adverse climate effects (Fischer, Shah, Tubiello, & van Velhuizen, 2005).

Though our knowledge of how climate stress influences rural livelihoods is growing, previous studies have been limited by an inability to consider both on and off-farm livelihood strategies within the same context. Considering that most rural households engage in some combination of these strategies (Reardon, 1997), it is critical that we understand both how smallholders respond to climate stress as well as how on and off-farm strategies interact with one another. Further, few studies have explored whether livelihood decisions differ during short and long spells of climatic stress, despite our broader understanding that the length of stress has a measurable impact on adaptation approaches (Senaka Arachchi, 1998).

Our research addresses these questions by analyzing a spatially integrated dataset consisting of longitudinal household survey

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data collected in 2003 and 2013 in rural Uganda and gridded temperature and precipitation data developed by the University of East Anglia Climatic Research Unit (CRU). First, we examine livelihood responses to annual and decadal climate anomalies, considering on-farm strategies as well as off-farm activity diversification. We then explore whether smallholders engage in on-farm strategies as a substitute for, or complement of, diversification into off-farm income strategies. Finally, we investigate whether these on and off-farm livelihood strategies are effective for improving household agricultural productivity, a major element of most rural households' livelihoods, during periods of climate stress.

Broadly, we find that smallholders respond differently to annual and decadal climate anomalies. In the short run, they are able to manage heat waves by investing more heavily in agriculture and engaging in part-time off-farm labor. In the long run, however, high temperatures are associated with reduced agricultural income and a reduced involvement in off-farm income generating activities. Further, smallholders generally engage in a combination of off-farm activities and on-farm strategies. In sum, we observe that on-farm strategies are largely successful in mitigating the harmful agricultural implications of climate stress in the short term but that these strategies are insufficient to avoid declining crop incomes during lengthy periods of above average temperatures. Given evidence that sub-Saharan Africa will experience increasing temperatures over the next century, our findings suggest that new livelihood strategies will be necessary if smallholders are to successfully adapt to global climate change.

2. Rural livelihoods in the context of climate change

Our research draws upon two related literatures—research on on-farm agricultural practices and research examining livelihood diversification into off-farm activities. Each of these literatures offers important insights into an aspect of smallholder livelihoods, which are typically composed of both on-farm (e.g. agriculture, livestock rearing) and off-farm (e.g. small business, wage labor) dimensions (Barrett, Reardon, & Webb, 2001). The combination of on and off-farm livelihood strategies can decrease the vulnerability of rural households by distributing risk (Ellis, 2000) and can provide households with a form of self-insurance (Barrett et al., 2001).

On-farm livelihood strategies employed by smallholders include cropping decisions, agricultural intensification, agricultural extensification, and on-farm diversification into livestock rearing. To reduce risk, smallholders may plant additional types or varieties of crops (Di Falco, Veronesi, & Yesuf, 2011). Some smallholders may also choose to plant more drought-resistant crops or to focus their agricultural production on staple crops rather than cash crops, in order to provide a consumption smoothing effect and reduce household food insecurity (Moniruzzaman, 2015). In addition to crop choice, smallholders may also vary the timing of crop planting. In this case, smallholders may plant a portion of their crops during the conventional planting period while reserving the remainder of their seeds to plant later, in case the first sowing fails (Di Falco et al., 2011). Along with these management approaches, smallholders may intensify their agricultural production through the input of crop amendments (e.g. inorganic fertilizer, manure, crop residue) or the investment of additional hours of labor (Scoones, 2000). If land is available, smallholders may also extensify, extending their cultivated land and increasing the odds that some percentage of their crop may survive during poor agricultural conditions (Paavola, 2008). Finally, some smallholders may invest more in livestock, diversifying their on-farm livelihood approach from cultivation to mixed cultivation and livestock rearing (Yesuf, di Falco, Deressa, Ringler, & Kohlin, 2008).

Smallholders also have the option of diversifying their livelihood into off-farm activities. Scholars have generally observed that livelihood diversification into off-farm activities increases livelihood security and improves farm efficiency (Mehta, 2009). Across sub-Saharan Africa, off-farm income accounts for around 35% of household income on average (Haggblade, Hazell, & Reardon, 2010). Off-farm livelihood diversification can include owning a small business (e.g. roadside stand, butchery, tailor shop), performing unskilled (e.g. farm labor) or semi-skilled labor (e.g. carpentry, brick-laying, technician), providing transportation (e.g. driving a motorcycle taxi), or seeking wage labor (e.g. working at a store, teaching, medical professional) (Smith, Gordon, Meadows, & Zwick, 2001). Off-farm livelihood diversification can occur at the household level, with some members of the household focusing on agriculture while others pursue off-farm labor, or at the individual level, with an individual supplementing on-farm strategies with off-farm income generating activities (Ellis, 2000). Some scholars have theorized that household livelihood diversification is a sign of a robust household that can afford to strategically distribute household human capital while individual activity diversification suggests that a household is scrambling to make ends meet and thus preventing household members from specializing (Ellis, 2000; Little, Smith, Cellarius, Coppock, & Barrett, 2001; Reardon, Taylor, Stamoulis, Lanjouw, & Balisacan, 2000). These strategies are not mutually exclusive, however. Household income diversification may come from individual activity diversification in addition to household division of labor (Bryceson, 2002).

Though many forms of stress can impact smallholder livelihood strategies, climate stress is of particular concern for sub-Saharan Africa. Climate change is predicted to reshape the agricultural landscape of the region, threatening the success of current regional staple crops and broadly reducing agricultural productivity (Lobell et al., 2008; Teixeira, Fischer, Van Velthuizen, Walter, & Ewert, 2013). Further, heat stress elevates the adverse human health effects of agricultural labor (Heal & Park, 2016). The rising temperatures and shifts in precipitation patterns that will result from climate change are especially harmful in rural contexts because they can produce aggregate rather than idiosyncratic household shocks (Günther & Harttgen, 2009). When a household is impacted by an idiosyncratic shock, such as the death of a family member, the community is likely to have the capacity to provide support. When the whole community or region is devastated by an aggregate shock such as extremely high temperatures, however, all individuals are affected to some degree and therefore cannot provide the same kind of social safety net (Samphantharak & Chantarat, 2015).

In response to climate stress, smallholders generally employ some combination of a shift in on-farm strategies and an increase in diversification into off-farm income generating activities (Fischer et al., 2005; Paavola, 2008). Much of the research interrogating the relationship between climate stress and livelihoods has focused on agriculture, as it is directly influenced by adverse climatic conditions. Recent literature examining climate variability and agricultural strategies has largely focused on the interaction between crop choice and rainfall. During periods of high rainfall, researchers have observed that farmers tend to plant a greater proportion of drought-sensitive crops (Cho, McCarl, & Wu, 2014; Moniruzzaman, 2015). Further, studies have found that periods of drought are associated with a shift away from permanent and cash crops toward staple crops, which are less valuable but can provide households with food security (Salazar-Espinoza, Jones, & Tarp, 2015). In one of the few studies that have examined temperature effects on crop choice, researchers determined that during periods of heat stress farmers plant a higher proportion of drought and heat tolerant crops (Cho et al., 2014).

In addition to crop choice, climate anomalies are associated with crop diversification. During droughts, farmers are more likely

to increase crop variety in order to increase production (Di Falco, Bezabih, & Yesuf, 2010; Lei, Liu, Zhang, & Luo, 2016). Though crop diversity may increase, the crops being chosen during periods of poor rainfall are generally those that are more drought-resistant and therefore less risky (Di Falco & Bezabih, 2012). Farmers have been noted to react to rainfall variability by diversifying their crop portfolio, especially during seasons of low rainfall (Bezabih & Sarr, 2012). Researchers have also observed qualitatively that, in response to drought, farmers intensify agriculture through increased labor and extensify cultivated land (Paavola, 2008). In addition to these agricultural strategies, previous research has revealed that some smallholders respond to changes in their climate by diversifying from crop production into mixed crop and livestock systems (Di Falco et al., 2011).

Examining the limited research on the relationship between climate stress and diversification into off-farm livelihoods, we once again find that most of the focus is on rainfall as a dimension of climate. Researchers find that households may be more likely to engage in non-agricultural labor during periods of drought (Paavola, 2008; Porter, 2012; Rose, 2001). Agricultural households have also been observed to be more involved in non-agricultural activities in areas with greater rainfall variability (Bandyopadhyay & Skoufias, 2015; Ito & Kurosaki, 2009; Kochar, 1999; Menon, 2009; Rose, 2001).

Our research contributes to the existing literature in a number of ways. First, it examines both on-farm livelihood strategies and off-farm livelihood diversification in response to climate anomalies in the same context and using the same data sources, an approach which has previously been employed primarily in the qualitative literature (Paavola, 2008). Second, much of the focus of past research has been on the influence of rainfall on livelihoods through the agricultural productivity pathway. Few studies have explored the dynamics between temperature and livelihood diversification, though recent research suggests that rising temperatures may be the most detrimental dimension of global climate change (Carleton & Hsiang, 2016). This is because temperature, unlike precipitation, has the potential to influence livelihoods both through an agricultural pathway as well as through human health and labor productivity pathways. Third, we examine the impacts of both short term and long term climate anomalies on livelihood diversification. Though previous research indicates that the length of climate stress may have different effects on adaptation approaches, there has been limited research on this topic in the context of rural livelihoods (Senaka Arachchi, 1998). Fourth, our study goes beyond examining crop choice, the predominant agricultural outcome in the literature, to look at the impact of climate stress on agricultural inputs and labor intensification. Finally, we also explore associations between climate anomalies and household income diversification as well as individual activity diversification, providing us with the opportunity to assess whether divergent processes for household and individual livelihood diversification exist in the context of climate change (Ellis, 2000; Scoones & Toulmin, 1998).

3. The Ugandan context

To examine the relationship between rural livelihoods and climate anomalies, we analyze a dataset consisting of gridded climate data and household survey data from eight districts and nine different agro-ecological zones across Uganda (see Fig. 1). These agro-ecological zones are classified as warm arid or sub-humid tropical zones, with mean temperatures ranging from 15 to 30 degrees C and total precipitation ranging from 750 mm to 1500 mm annually. In the northern region, Uganda has one rainy season and one dry season, while in southern Uganda, rainfall is bimodal, with long rains from March to May and short rains from September to December (Ronner & Giller, 2013).

Considering the socioeconomic and demographic composition of the country, Uganda's population density, as in many parts of East Africa, is much higher than in other parts of the continent (United Nations Development Programme, 2014). Uganda also exhibits sub-optimal crop productivity and high rates of poverty (Pender, Place, & Ehui, 2006). Further, in spite of the overall shift of the economy toward non-agricultural sectors, nearly 80% of the population remains employed in agriculture and over 80% of the population lives in a rural area (Uganda Bureau of Statistics, 2014). The majority of Ugandan agriculture takes place on smallholder plots with mixed cropping systems (Rogerson & Gollin, 2010). Ugandan agriculture is predominantly rain fed, with less than five percent of all farmers employing irrigation systems. Though some Ugandan farmers use agricultural amendments and inputs (e.g. chemical fertilizer), the rates of usage remain very low, with fewer than three percent of all farmers adding inorganic nitrogen, phosphorus, or potassium to their soil and only roughly ten percent of all Ugandan farmers using any form of pesticide, fungicide, or herbicide (Sheahan & Barrett, 2017). Ugandan agriculture also relies heavily on human and animal labor—fewer than three percent of all Ugandan smallholders own or rent a tractor (Sheahan & Barrett, 2017). After harvest, smallholders often sell some of their yield, but most of this production is for domestic markets. Export (cash) crops, which include coffee, tea, cotton, and sugar, generally account for less than ten percent of the cropped area in Uganda. The major food crops consist of matoke (cooking banana), maize, cassava, yams, and other root crops (Rogerson & Gollin, 2010).

Alongside agriculture, Uganda, livelihood diversification is a conventional element of rural livelihoods (Barrett et al., 2001). One out of ten rural workers are engaged in the non-farm or informal sectors while a similar percentage of rural laborers engage in wage labor (The World Bank, 2013). However, in these same rural areas, non-farm income generally accounts for about 40% of household income (Nagler & Naudé, 2017). Non-farm livelihood activities include small-scale enterprises (e.g. sale of alcohol and food), cottage industries and crafts (e.g. brick making, carpentry, construction), fish trading, crop trading, and service based enterprises (e.g. lodging houses, restaurants, bars) (Smith et al., 2001). Previous research suggests that wealthier households, those with more land and greater overall income, are also those more likely to have the resources to engage in non-farm enterprises in Uganda (Nagler & Naudé, 2017).

4. Data and methods

This study uses two waves of household survey data collected in 2003 and 2013. The first wave was a collaboration between researchers from International Food Policy and Research Institute (IFPRI) and the National Agricultural Research Laboratories (NARL) of Uganda. The 2003 sample was a two-stage clustered randomized sample of 850 farm households from 120 communities in eight different districts across Uganda, chosen to be representative of nine of the major agro-ecological zones in the country (see Fig. 1). These household are a subsample of those surveyed by the Uganda Bureau of Statistics (UBOS) for the Uganda National Panel Survey (Nkonya et al., 2008). The second wave of data was collected in 2013 by a team of researchers from IFPRI, NARL, the University of North Carolina at Chapel Hill (UNC-CH), Cornell University, and Purdue University, targeting the same households.

In both waves, Ugandan enumerators collected survey and spatial data at the household, plot, and community levels, and gathered plot-level soil samples for laboratory soil analysis. In the

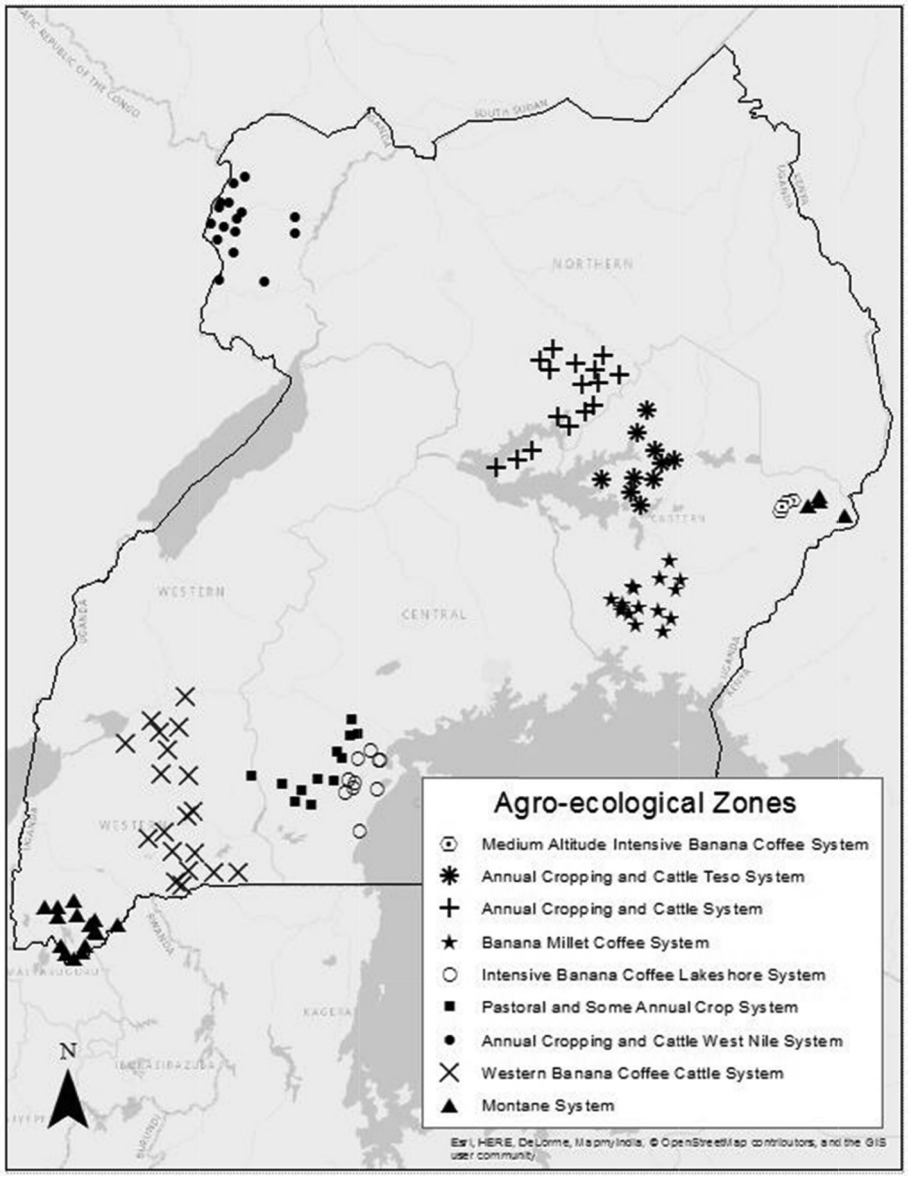

Fig. 1. Map showing study community locations within nine distinct agro-ecological (cropping regime) zones.

second wave of the survey, enumerators returned to 727 of the 849 households interviewed in 2003. Supplementary analysis reveals that the 122 households not interviewed are not systematically different in any observable way from households in the panel. In addition, in cases where original household members had split off to form their own households between the first and second waves, the new households were interviewed if the located within the same parish. Including these split-off households, enumerators collected survey data from 831 households in 2013.

We also draw upon gridded temperature and precipitation data from the University of East Anglia Climatic Research Unit's (CRU) time-series 3.24, produced by the interpolation of data from a global network of over 4000 weather stations. CRU is a monthly global dataset with a resolution of 0.5 degrees (approximately 50 km at the Equator) (UEACRU et al., 2013). These data are viewed as a highly reliable source of climate measures in Africa (Zhang, Kornich, & Holmgren, 2013). The CRU data were also chosen because the precipitation values provided by CRU are considered a more spatially and temporally accurate representation of mid-latitude precipitation variation than other climate products (Los, 2015).

In order to examine how smallholders cope with short and long term climate anomalies, we first construct measures of on-farm agricultural strategies and off-farm livelihood diversification using the survey data. From these data, we also construct measures of household capital as well as additional control variables. We then use GIS to extract community-level measures of temperature and precipitation from the CRU data. After combining the survey and climate data, we analyze this dataset using multivariate approaches appropriate for our data structure. Finally, to provide clarity about the relationships we observe in our analysis, we examine the relationship between climate arability and plot-level crop productivity and value.

4.1. On-farm strategies

Our plot-level measures of agricultural strategies include the number of distinct crops planted over the course of the year, whether the household applied organic fertilizer in the past year, and the number of hours of labor a household invested in a plot in the past year (see Table 1). We also considered the relationship between climate stress and household livestock ownership as well

Table 1
Descriptive statistics and description of variables.

	N	Mean	SD	Min	Max	Description
Household characteristics (household-year)						
Household livelihood diversification	1314	0.69	–	0	1	0 = Primary and secondary sources of household income are on-farm, 1 = Either primary or secondary source of household income is off-farm
Female headed household	1314	0.22	–	0	1	Female headed household
Age of head of household	1314	45.82	14.70	15	105	Age of head of household
Formally educated head of household	1314	0.83	–	0	1	Head of household has formal education
Agriculturally trained head of household	1314	0.30	–	0	1	Head of household has participated in agricultural training
Household size	1314	6.27	3.05	1	26	Number of people in the household
Distance to market	1314	3.69	3.50	0.02	18.51	Distance to the nearest market (kilometers)
Secure land tenure	1314	0.33	–	0	1	1 = Freehold or leasehold land tenure (more secure), 0 = Customary land tenure (less secure)
Household asset value	1314	5235	9045	94	61,889	Total estimated value of household assets including farm equipment, buildings, land, and material goods (USD)
Household livestock value	1314	594	1645	0	21,853	Total estimated value of household livestock (USD)
Individual characteristics (person-year)						
Individual livelihood diversification	2880	0.72	–	0	1	0 = Primary and secondary activities are on-farm, 1 = Either primary or secondary activity is off-farm
Female	2880	0.54	–	0	1	1 = Female, 0 = Male
Age	2880	39.66	15	18	105	Age of individual
Plot characteristics (plot-year)						
Distance from plot to home	2703	2656	353	0.59	4702	Distance from the plot to the homestead (meters)
Area of plot	2703	0.34	0.56	0.01	15.40	Area of a plot (hectares)
Soil fertility	2703	4.91	1.82	0	10	Plot level soil fertility index derived from PCA of measured soil characteristics
Applied organic fertilizer	2703	0.16	–	0	1	Applied any organic fertilizer to a plot
Total hours of labor	2703	478	634	7	3870	Total hours of labor applied to a given plot in a year by family and non-family/hired labor
Number of crops planted	2703	2.25	1.29	1	10	Total number of distinct crops planted over the course of the year
Kilograms of crops produced per hectare	2703	6781	14,468	51	99,829	Total reported kilograms of crops produced per hectare (kg/ha)
Estimated monetary value of crops per hectare	2703	976	1898	9	12,870	Total estimated monetary value of crops produced per hectare (USD/ha)
Climate anomalies (community-year)						
Mean annual precipitation	122	1259	153	926	1639	Mean annual precipitation, 1980–2013 (millimeters)
Mean annual temperature	122	22.26	2.40	16.72	26.09	Mean annual temperature, 1980–2013 (Celsius)
One-year precipitation anomaly	244	0.76	0.78	−1.21	2.33	Z-score of one-year total precipitation relative to 1980–2013
One-year temperature anomaly	244	0.94	0.91	−0.26	2.17	Z-score of one-year average temperature relative to 1980–2013
Ten-year precipitation anomaly	244	0.75	0.77	−1.37	2.08	Z-score of ten-year annual average precipitation relative to 1980–2013
Ten-year temperature anomaly	244	0.63	0.78	−0.28	1.52	Z-score of ten-year annual average temperature relative to 1980–2013

as agricultural land extensification, but neither of these approaches were significantly affected by climate anomalies and the results are not shown. Our measures are all constructed using the plot-level agricultural component of the household survey. To build our measure of the number of the crops planted over the course of the year, we generate an indicator for each unique crop planted in each plot in either of the two seasons and sum together these indicators. On average, a plot was planted with 2.25 different crops over the course of the year, suggesting that on average in one season a plot was mono-cropped while smallholders practiced some kind of mixed cropping in the other season. There is, however, a large range in the number of crops planted in a plot over the course of the year, with the smallest number being one crop (e.g. for perennials like banana) and the largest being ten distinct crops.

To operationalize whether or not a household applied an organic fertilizer (e.g. crop residue or manure) we generate an indicator variable where zero represents no organic fertilizer application and one represents some organic fertilizer application. In our sample, 16% of plots were organically fertilized during the year. We chose to use an indicator variable for organic fertilizer application rather than a value for the amount of fertilizer applied to each plot because that information was not collected as part of the plot-level agricultural survey. We focus on organic fertilizer rather than non-organic fertilizer because fewer than 3% of the plots in our sample were fertilized using non-organic fertilizer.

Finally, we sum together the number of hours of labor from family members, neighbors, and hired laborers during both agricultural seasons to calculate the total number of hours of labor applied to each plot in a given year. Though the amount of labor applied to a plot ranges greatly, the average number of hours of labor applied to a plot over the course of the year is 543 hours, or roughly two and a half full person-months of labor assuming a 50-hour work week.

4.2. Off-farm livelihood diversification

To construct our measures of off-farm livelihood diversification, we use information from the household roster as well as a module on household sources of income. From the roster, we extract information on the primary and secondary activities performed by each member of the household ages 18 and above, and use this to construct our measure of individual livelihood diversification. Individuals whose primary and secondary activities were on-farm, including working in agriculture or livestock tending, are assigned a value of zero to represent that they are not involved in a diversified livelihood strategy. The remainder of individuals typically reported one on-farm livelihood strategy as well as one off-farm strategy, such as in hospitality or transportation. These individuals are assigned a value of one to indicate that they are engaged in diversified livelihood activities. Nearly 75% of all individuals participated in a diversified livelihood approach.

The module on household sources of income provided us with information about the primary and secondary sources of household income. As with the individual livelihood diversification measure, households are assigned a livelihood diversification value of zero if their primary and secondary income sources are on-farm,

either agriculture or livestock-based. We chose not to disaggregate on-farm livelihood diversification into purely agriculture households and households that have both agriculture and livestock because the majority of households in our survey data operate on-farm using a mixed cropping-livestock system. Those households where one or both of their income sources are from an off-farm activity are assigned a livelihood diversification value of one to represent that they are involved in off-farm livelihood diversification. Similar to individual livelihood diversification, almost 70% of all households in our sample employed a diversified livelihood strategy.

4.3. Climate measures

Our measures of temperature and precipitation are extracted from annual CRU data. To measure local deviations from the historical climate, we transform these values into climate anomalies, defined as the z-score of the mean temperature or total annual precipitation relative to a 1980–2013 reference period. Specifically, we link both one-year and ten-year periods of climate data to the end date of our survey measurements in December 2002 and 2012 (The questions were asked in 2003 and 2013 in reference to the previous year). We then compute z-scores comparing these one-year and ten-year periods to all other periods of the same length within the reference period. We refer to these as the one-year and ten-year climate anomalies.

We observe that average annual precipitation in our study areas ranges from 926 mm to 1,639 mm while the average annual temperature ranges from 16 °C to 26 °C. Further, we find that precipitation appears to have varied significantly both in the long and short term from the 30-year climate average, with some communities experiencing periods of above average rainfall while others have experienced droughts. Conversely, nearly all temperature anomalies have involved above-average temperatures, reflective of the global increase in temperature resulting from climate change (IPCC, 2014) (see Fig. 2 for graphs of temperature and precipitation trends and anomalies).

4.4. Controlling for household capital and adaptive capacity

The survey data are also used to generate a set of controls based on the sustainable livelihoods framework (Ellis, 2000; Scoones, 2000). To adjust for differences in household assets, we consider relevant aspects of four of the five different types of capital described in the framework (human, physical, financial, and natural capital[1]). Our measures of human capital include whether the head of household has any formal education, whether the head of household has participated in technical agricultural training, and the number of household members (household size). We measure financial and physical capital simultaneously through the estimated value of household assets, which includes farm equipment as well as the value of home and durable goods. We also include a measure of the estimated value of all livestock owned by a household.

Natural capital is measured through area of agricultural land, distance from a plot to household (as more proximate plots require less labor to maintain), and area-weighted measures of soil fertility. Our soil fertility index is generated through principal components analysis. We construct an index of four measured soil properties: pH, organic matter, phosphorus, and available potassium after log transforming those soil properties that were strongly right skewed, to prevent outliers from influencing the outcome of the analysis. Greater than 50% of the variance is explained by the first principal component, indicating that it is a suitable measure of soil fertility. The value of the first principal component is then rescaled to range from 0 to 10. For the household level analysis, we also weight the plot-level soil fertility measures by the relative plot size to the total amount of land owned by a household.

Alongside these different types of household capital, we include variables measuring the age of the head of household (or individual), gender of the head of household (or individual), and distance to the nearest market. These attributes can all contribute to variation in vulnerability and adaptive capacity (Adger, 2006). Age and gender both shape access to livelihoods and resources from a power relations standpoint (Nelson, Meadows, Cannon, Morton, & Martin, 2002). Market distance modulates access to resources and opportunities (Kotir, 2011). Smallholders located further away from towns are likely to have reduced opportunities to obtain off-farm employment.

4.5. Regression approaches

To measure the influence of climate on livelihoods while accounting for potential confounders, we use a fixed effects regression approach as described in detail below and summarized here. Intuitively, we take advantage of climate variation across time and space to examine climatic influences on livelihoods while removing both the time-stable effects of place as well as the changing national context. In this analysis, the counterfactuals include the same district across time (with the overall national pattern of change removed) as well as other districts at the same time (with the time-stable effects of place removed). To account for smaller-scale differences in individuals, households and communities across time and space we also include a large se of controls at these scales. Because climate anomalies are effectively random over space and time (with the exception of increasing temperature anomalies over time, accounted for by our approach), anomalies can be interpreted as natural experiments and our results therefore have a causal interpretation (Nordkvelle, Rustad, & Salmivalli, 2017). This interpretation is consistent with a large and growing literature that has used fixed effects regression approaches to measure causal climatic effects on social outcomes (Burke, Hsiang, & Miguel, 2015; Mueller, Gray, & Kosec, 2014).

To implement this, we first stack the 2003 and 2013 rounds to create analytical datasets of plot-years, person-years and household-years for particular outcomes. This approach allows us to examine adaptation over time in the same spatial context but without restricting our analysis to households, plots and individuals observed at both time points. We then employ multivariate regression approaches to analyze these datasets.

First, to explore on-farm livelihood approaches, we employ four different regression approaches determined by the outcome of interest. To estimate the number of crops planted, a count variable, we use a Poisson regression. We examine whether or not households applied organic fertilizer to a plot through a logistic regression approach. To assess the log-transformed total hours of labor invested in a plot, we use ordinary least squares. Each of these analyses is performed using plot-specific data. Second, we use logistic regression to estimate the impact of short and long-term climate anomalies on off-farm diversification at the individual and household levels, controlling for differences in capital and adaptive capacity. We also employ logistic regression models to examine whether on-farm and off-farm livelihood strategies are complementary or substitutional. Finally, we use ordinary least squares to investigate the relationship between climate variables, livelihood strategies, and crop productivity, operationalized as crop kilograms harvested per hectare and estimated monetary value of crops grown per hectare.

[1] We do not include any measures of social capital as our survey did not collect sufficient information to measure social capital at the household leve1.

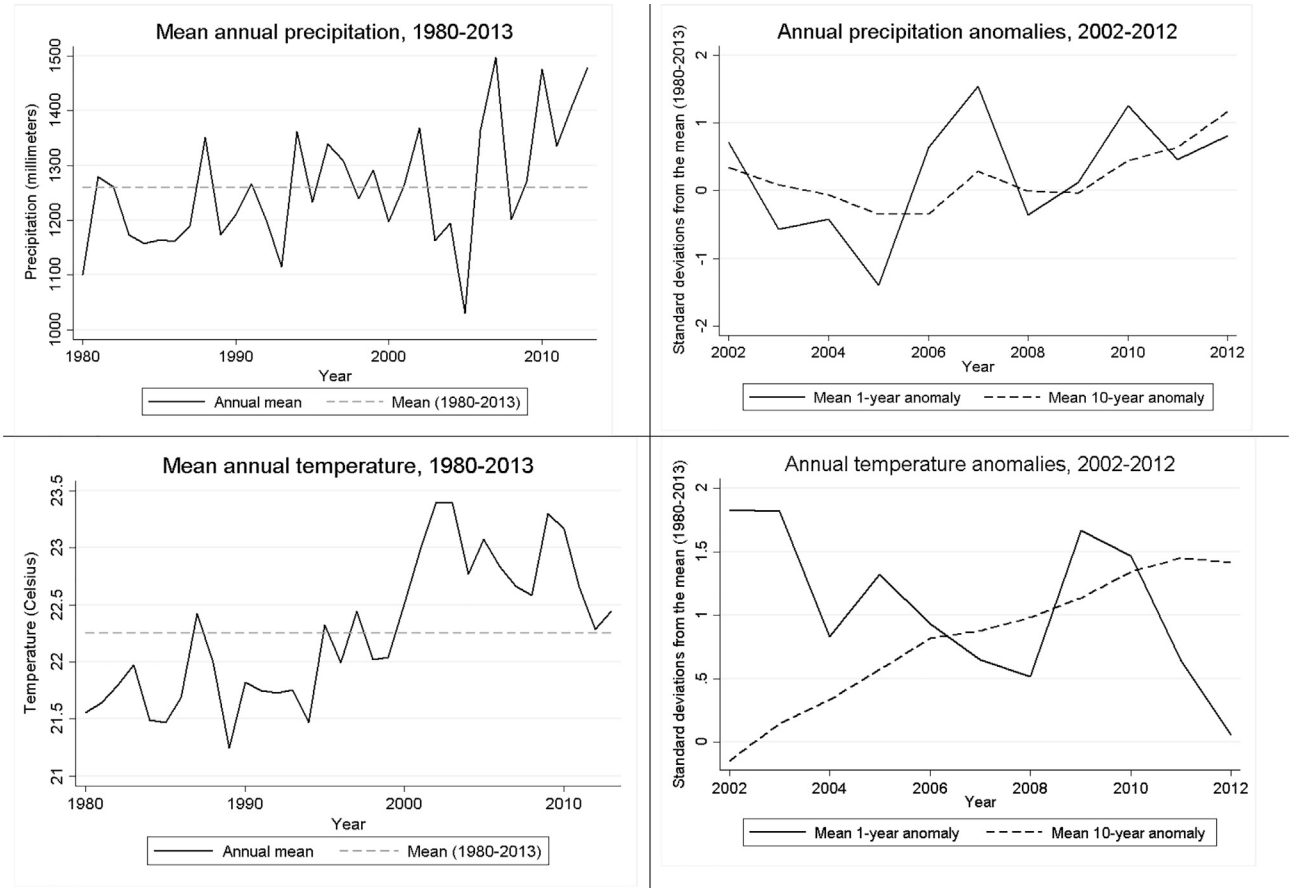

Fig. 2. Temperature and precipitation trends and anomalies.

For all models, we include district fixed effects to account for agro-ecological, socio-demographic, and other unmeasured differences between the districts. Year fixed effects are included in all models to adjust for differences between the two years of data collection. For the crop productivity and agricultural intensification analyses, fixed effects for crop type (e.g. legumes, cash crops, tubers, cereals, banana) are included to adjust for crop-specific differences in yield and market value. The inclusion of these fixed effects mean the results can be interpreted as comparing two households in the same district in the same year who were exposed to different climatic conditions. Standard errors are clustered at the community level in all analyses. Logistic regression coefficients are shown in all tables as odds ratios while Poisson regression coefficients are displayed as incidence rate ratios and ordinary least squares coefficients are displayed as raw values. In all regressions, household asset values and household distance to nearest market are log transformed to reduce skewness.

5. Results

The results of our analysis can be found in Tables 2 through 4. Table 2 presents the effects of climate anomalies on four major types of on-farm livelihood strategies. Table 3 shows both the effects of climate anomalies on household and individual off-farm livelihood diversification as well as the relationship between on-farm and off-farm livelihood diversification. Finally, Table 4 highlights the influence of climate anomalies on crop productivity, both with and without the implementation of on and off-farm livelihood strategies. In the following section, we will first explore the overall significance of short and long-term temperature and precipitation anomalies for on and off-farm smallholder livelihoods, and the relationship between them, in rural Uganda. We will then address the relationship between climate anomalies and specific on and off-farm livelihood strategies. To conclude, we will briefly discuss the role that additional sociodemographic and biophysical factors play in shaping household adaptive capacity.

Very broadly, we find that climate anomalies do have a significant impact on both the on-farm and off-farm dimensions of rural smallholder livelihoods (see Figs. 3 and 4). Above average temperatures may benefit some households in the short term, likely due to above average market prices, but after a decade of above average temperatures, agricultural crop yield declines regardless of whether or not households increase their investment in on and off-farm strategies. Conversely, long and short periods of above-average precipitation, which result in reduced need for on-farm labor, provide household members with the opportunity to spend more time pursuing off-farm livelihood activities.

Considering the nature of the relationship between investment in on-farm strategies and diversification into off-farm livelihoods, we find mixed results (Table 3). Households that report applying organic fertilizer are indeed less likely to diversify into off-farm livelihoods. This finding suggests that households may substitute costlier on-farm investments for off-farm diversification. On the other hand, we do not see any significant relationship between crop diversification or hours of on-farm labor with the odds of diversifying into off-farm livelihoods. Likewise, we find no statistically significant relationship between investment in on-farm strategies and individual diversification into off-farm livelihoods. Households appear to draw upon a combination of on and off-farm approaches to construct a sustainable livelihood strategy.

Table 2
Regressions predicting on-farm management strategies (plot-year level).

	Number of crops planted (Incidence rate ratios)		Applied organic fertilizer (Odds ratios)		ln(Total hours of labor) (Coefficients)	
	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly
Climate anomalies						
Precipitation	1.030*	0.948***	1.491+	1.278*	−0.201**	−0.172**
Temperature	1.236***	0.707**	5.761***	0.013***	−0.031	0.791
Household characteristics						
Age of head of household	1.000	1.000	1.000	1.000	0.004+	0.004+
Female headed household	1.018	1.013	1.151	1.186	−0.051	−0.084
Formally educated head of household	1.002	1.004	1.431+	1.478*	0.031	0.023
Agriculturally trained head of household	1.003	1.003	0.824	0.829	−0.035	−0.054
Household size	0.999	0.999	1.069*	1.068*	0.031***	0.027**
ln(Household asset value)	1.004	1.002	1.017	1.009	−0.086**	−0.082*
ln(Household livestock value)	1.002	1.002	1.092**	1.091**	0.036**	0.036**
ln(Distance to market)	1.002	0.997	0.929	0.946	0.058+	0.041
Secure land tenure	1.013	1.012	1.162	1.171	0.133*	0.125+
Plot characteristics						
ln(Distance from plot to home)	0.985**	0.985**	0.590***	0.591***	0.048**	0.045**
ln(Plot area)	1.040***	1.039***	1.194*	1.184*	0.377***	0.386***
Soil fertility	1.006	1.003	0.979	0.984	0.049**	0.046**
Observations	2729	2729	2708	2708	2528	2528
R-squared					0.401	0.400

District fixed effects, year, crop type fixed effects, climate means, and constants included but not shown.
Standard errors are robust and clustered at the community level.
*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.
+ $p < 0.1$

Specifically examining short-term temperature anomalies, we find that households plant a greater number of distinct crops and invest in the application of organic fertilizer during years of above average temperatures (Fig. 4; Table 2). By employing these management strategies, households are able to increase crop productivity (Table 4). Years of above average temperatures are also associated with lower odds that one of the top two income sources of a household will come from an off-farm livelihood strategy, but higher odds that individuals will participate in off-farm activities (Fig. 3; Table 3). These results suggest that households may be prioritizing on-farm strategies during these times, to take advantage of high market prices induced by the idiosyncratic shocks of uneven crop failures. Crop failures increase market demand and may lead to higher market prices for crops. These resources may in turn provide individuals with the resources to pursue off-farm activities.

In the end, however, a decade of above average temperatures is associated with lower odds of individual activity diversification, though heat stress appears to have no long-term impact on household-level diversification (Fig. 3; Table 3). These long periods of high temperatures are also associated with reduced crop value, likely due to heat induced crop failure and a possible increase in agricultural pests (Carleton & Hsiang, 2016) (Table 4). Without sufficient crop income, households may not be able to afford the opportunity cost for individuals to diversify into off-farm livelihood strategies (Barrett, Bezuneh, & Aboud, 2001). Long spells of above average temperatures also reduce the number of crop types planted as well as the odds of applying organic fertilizers (Fig. 4; Table 2). During these periods of heat stress, households may concentrate on cultivating a limited number of staple crops, to smooth household consumption (Salazar-Espinoza et al., 2015).

Turning to precipitation, we observe that precipitation anomalies lead to reduced farm labor and, in turn, increased odds of individual livelihood activity diversification (Figs. 3, 4; Tables 2, 3). A year of high rainfall is also associated with increased crop productivity (Table 4). During these years, households can achieve the same crop productivity without investing in as much labor, providing household members with the time and resources to diversify into off-farm livelihood activities. These findings suggest that in periods of drought, households have to invest more labor in agriculture to maintain production, as has been observed descriptively in previous research (Paavola, 2008).

The effect of a decade of high rainfall on on-farm strategies is similar to that of a year of above average rainfall. Households report fewer hours of on-farm labor and increased odds of applying organic fertilizer. However, unlike during a single year of high rainfall, households report planting lower numbers of unique crops after a decade of above average precipitation (Fig. 4; Table 2). These periods may provide households with the confidence to grow a riskier crop portfolio without concern for drought (Salazar-Espinoza et al., 2015). Though household off-farm income diversification is not affected, individuals appear to be more likely to pursue off-farm livelihood activities during extended periods of above average rainfall (Fig. 3; Table 3). It is likely that when households have more resources and reduced labor needs, individuals are able to more easily access off-farm livelihood activities.

Household capital and adaptive capacity play an important role in shaping rural livelihoods. In regard to household capital, we observe that households with greater livestock, a key asset, have lower odds of household livelihood diversification. This finding is supported by research that argues that middle income households in sub-Saharan Africa have the highest livelihood diversification (Loison, 2015). Individuals from households with greater non-livestock assets, however, have higher odds of diversifying their livelihoods. Wealthier households may provide individuals with the initial resources they need to access non-farm labor opportunities (Ellis, 2000). Considering adaptive capacity, increased distance to market is associated with lower odds of individual and house-

Table 3
Logistic regression predicting odds of off-farm livelihood diversification with and without controls for on-farm management strategies (odds ratios) (household-year and person-year level respectively).

	Household livelihood diversification				Individual livelihood diversification			
	Without strategies		With strategies		Without strategies		With strategies	
	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly
Climate anomalies								
Precipitation	0.798	1.037	0.932	1.185	1.393*	1.283*	1.023	1.055
Temperature	0.306*	7.952	0.931	1.065	3.655*	0.016**	3.551***	0.232***
Individual characteristics								
Female					0.881+	0.884+	0.916	0.912
Age					0.996	0.996	0.983	0.979+
On-farm strategies								
Number of crops planted			0.918	0.929			1.031	1.040
Applied organic fertilizer			0.577**	0.577**			1.036	1.051
ln(Total hours of labor)			0.990	0.997			0.996	0.997
Household characteristics								
Age of head of household	0.995	0.994	0.995	0.995	0.995	0.995	1.009	1.013
Female headed household	0.873	0.879	0.906	0.916	1.224	1.242	1.205	1.200
Formally educated head of household	1.370***	1.360**	1.530***	1.520***	1.205*	1.212*	1.212*	1.209*
Household size	1.006	1.009	0.983	0.982	1.078**	1.078**	1.031	1.029
ln(Household asset value)	0.997	1.004	0.922	0.930	1.135+	1.132+	1.149*	1.158*
ln(Household livestock value)	0.720***	0.720***	0.830***	0.831***	0.983	0.985	1.014	1.013
ln(Distance to market)	0.773*	0.780*	0.833*	0.841*	0.647***	0.650***	0.864*	0.867*
Average household soil fertility	0.996	1.002	0.993	0.993	1.023	1.024	1.006	1.022
Secure land tenure	1.088	1.084	1.074	1.082	1.227	1.277	1.132	1.104
ln(Total agricultural area)	0.811**	0.814**	0.837*	0.826*	0.849*	0.849*	0.860+	0.853*
Observations	1331	1331	1240	1240	2817	2817	2639	2639

District fixed effects, year, climate means, and constants included but not shown.
Standard errors are robust and clustered at the community level.
*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.
+ $p < 0.1$.

hold livelihood diversification, likely because of the increased difficulty in accessing off-farm labor opportunities (Yamano & Kijima, 2011). We also find that female-headed households have lower crop productivity, perhaps due to restrictive gender norms and household labor expectations (Tibesigwa, Visser, Hunter, Collinson, & Twine, 2015). Few household characteristics are significantly associated with agricultural strategies, though we do observe that larger households with more livestock have increased odds of applying organic fertilizer and tend to engage in a greater number of hours of agricultural labor. This is unsurprising, as livestock provide a ready supply of inexpensive organic fertilizer and larger households have more individuals available to engage in agricultural labor.

6. Conclusions

We present empirical evidence that long and short-term climate anomalies have important influences on both major dimensions of rural smallholder livelihoods: on-farm strategies and diversification into off-farm activities. We find that smallholders can cope with high temperatures in the short term, but long periods of above average temperatures depress agricultural productivity and reduce opportunities for off-farm activity diversification. Further, below-average rainfall decreases agricultural productivity in the short term and lengthy droughts reduce individual activity diversification. Regardless of climate stress, we find that households commonly employ both on and off-farm livelihood strategies as part of a robust livelihood approach (Eakin, 2005). These findings highlight the complex and interconnected nature of on and off-farm livelihoods and provide strong support for a number of previous hypotheses regarding climate and rural livelihoods.

First of all, only a limited number of studies have examined the relationship between temperature anomalies and rural livelihoods, despite our growing awareness that high temperatures are likely to be one of the most harmful aspects of global climate change (Carleton & Hsiang, 2016). Our research demonstrates that temperatures significantly influence livelihood decisions. Further, temperature and precipitation are often correlated. As such, researchers who neglect to consider the implications of temperature anomalies alongside rainfall anomalies risk finding spurious associations.

In addition, our analysis illustrates that short and long term periods of climate stress have different impacts on household livelihood strategies, as suggested by previous research (Senaka

Table 4
OLS regressions predicting crop productivity (coefficients) (plot-year level).

	ln(Kilograms of crops produced/ha)				ln(Estimated monetary value of crops produced/ha			
	Without strategies		With strategies		Without strategies		With strategies	
	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly	One-year climate anomaly	Ten-year climate anomaly
Climate anomalies								
Precipitation	0.184***	−0.082+	0.199***	−0.011	0.191***	−0.065	0.233***	−0.002
Temperature	0.387*	−0.524	0.234	−0.364	0.790***	−1.557***	0.716***	−1.615***
Household characteristics								
Age of head of household	0.001	0.001	0.000	0.000	0.000	0.000	−0.001	−0.001
Female headed household	−0.217**	−0.216**	−0.166*	−0.156*	−0.198**	−0.204**	−0.146*	−0.142*
Formally educated head of household	−0.025	−0.015	−0.029	−0.021	−0.018	−0.007	−0.025	−0.013
Agriculturally trained head of household	0.059	0.071	0.082	0.096+	0.065	0.071	0.095+	0.105*
Household size	0.011	0.011	0.001	0.004	0.012	0.011	0.002	0.003
ln(Household asset value)	0.125***	0.118***	0.129***	0.124***	0.125***	0.118***	0.137***	0.131***
ln(Household livestock value)	0.018	0.017	0.018	0.017	0.029*	0.028*	0.025*	0.024*
ln(Distance to market)	0.025	0.022	0.013	0.015	0.003	−0.003	−0.008	−0.009
Secure land tenure	0.057	0.051	−0.005	−0.004	0.105	0.101	0.053	0.056
Plot characteristics								
ln(Distance from plot to home)	0.051*	0.053*	0.065**	0.069**	0.047*	0.050*	0.057*	0.061*
ln(Plot area)	−0.663***	−0.670***	−0.759***	−0.763***	−0.661***	−0.667***	−0.765***	−0.771***
Soil fertility	0.011	0.005	−0.019	−0.02	0.016	0.01	−0.015	−0.016
Livelihood strategies								
Diversified livelihood strategy			−0.008	−0.011			−0.011	−0.018
Number of crops			0.231***	0.233***			0.204***	0.207***
Applied organic fertilizer			0.267***	0.273***			0.238***	0.250***
ln(Total hours of labor)			0.230***	0.220***			0.251***	0.244***
Observations	2431	2431	2312	2312	2375	2375	2312	2312
R-squared	0.487	0.485	0.528	0.525	0.494	0.492	0.533	0.529

District fixed effects, crop type fixed effects, fallow fixed effects, year fixed effects, climate means, and constants included but not shown.
Standard errors are robust and clustered at the community level.
*** p < 0.001.
** p < 0.01.
* p < 0.05.
+ p < 0.1.

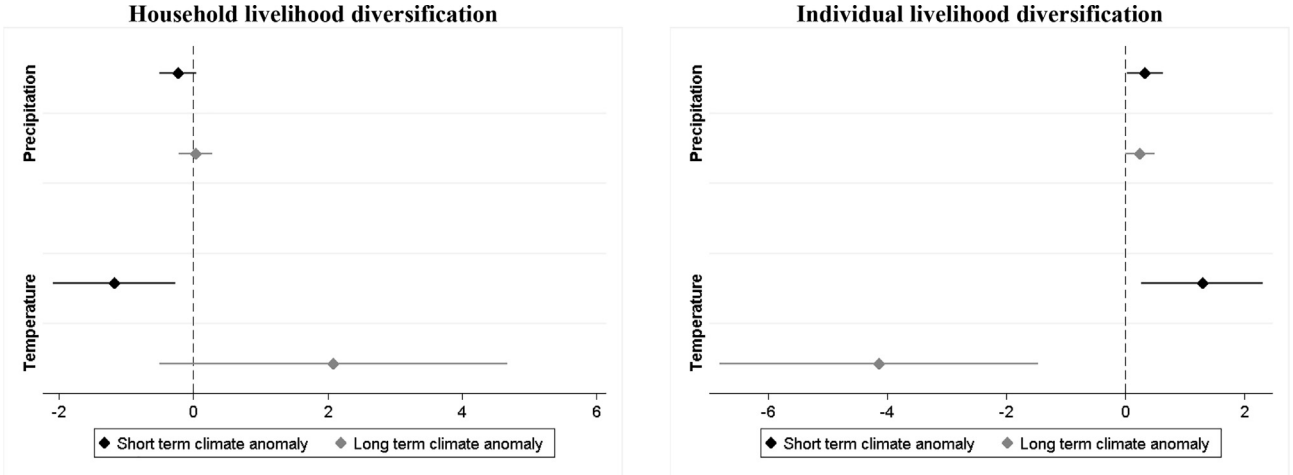

Fig. 3. Effects of temperature and precipitation anomalies on off-farm livelihood diversification (Coefficients).

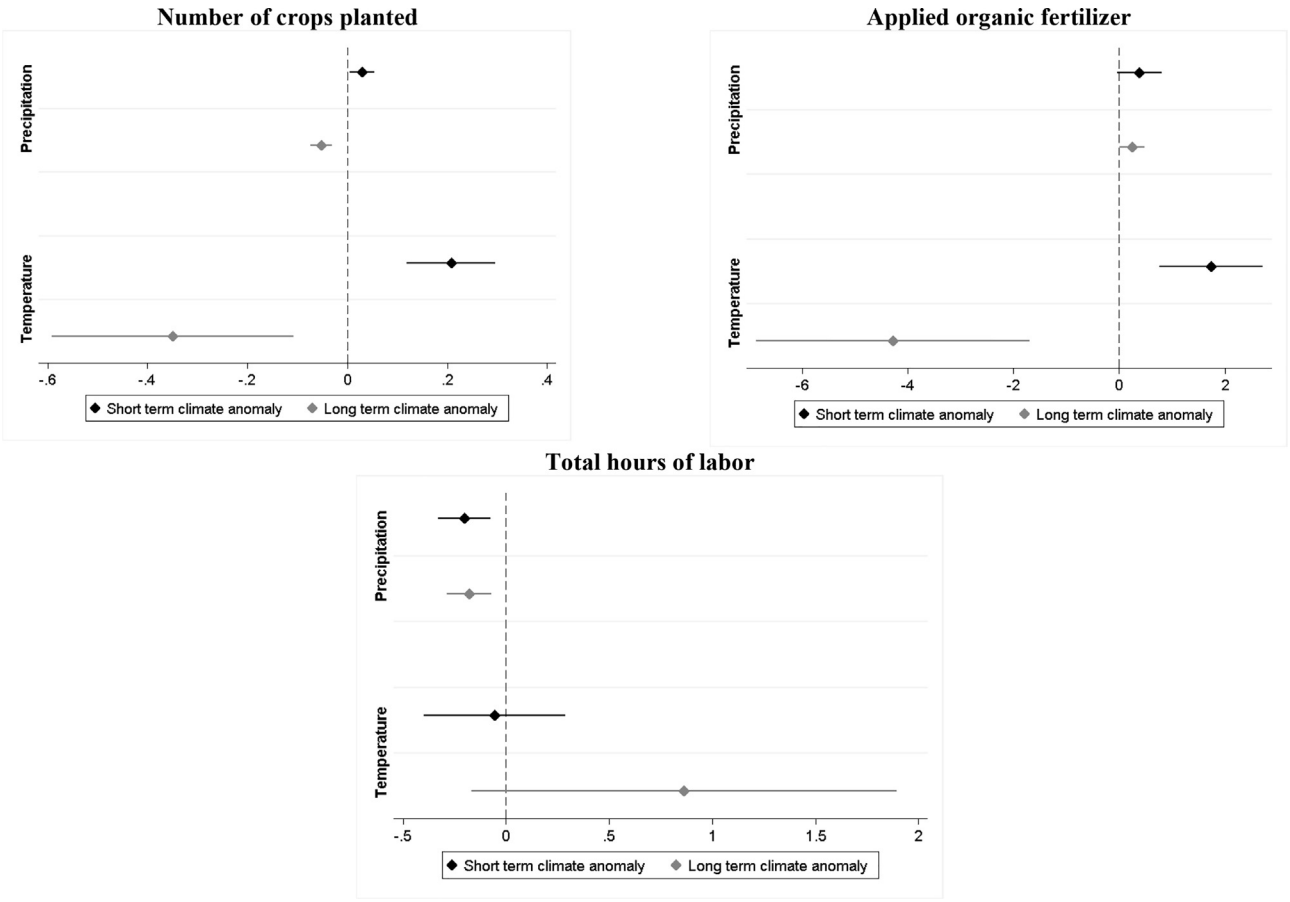

Figure 4. Effects of temperature and precipitation anomalies on on-farm livelihood diversification (Coefficients).

Arachchi, 1998). While smallholders can successfully cope with short periods of above average temperatures through on-farm inputs and off-farm activity diversification, this suite of strategies may not be sufficient to cope with long heat waves. These findings are concerning, considering that that high temperatures have a direct health impact on human labor capacity, as well as crop yield (Carleton & Hsiang, 2016). To better understand these dynamics, future work should consider both of these potential pathways for the impact of heat stress on rural livelihoods.

Our research also illustrates that smallholders employ different kinds of on-farm strategies in response to different dimensions of climate variation. To respond to short-term heat stress, for example, smallholders may apply soil inputs or diversify their crop portfolio. These approaches require resources to acquire the inputs or seeds but may not require much additional labor from the household. In the longer run, however, smallholders may shift to a limited crop portfolio of staple crops, which can provide a consumption smoothing effect that reduces household food insecurity (Moniruzzaman, 2015). Our observations suggest that studies that only consider one dimension of a robust agricultural strategy, such as crop choice, are likely to miss the broader picture of how smallholder households respond to climate stress. Future research should consider examining a greater range of on-farm management strategies and specific non-farm livelihood activities.

The generalizability of this study is limited by the single country and time period from which the data were collected. Regarding the analytical approach, we have taken great care to attempt to isolate the effects of climate from potential confounders, but it is nonetheless possible that our results are confounded by an unobserved factor that is correlated with climate but not driven by climate, such as specific socio-cultural, political, technological, or economic changes that occurred in Uganda between 2003 and 2013. Future research should examine this question across a range of contexts and periods, and consider additional analytic methods to isolate the effects of climate.

To conclude, our findings suggest that if temperatures continue to rise, smallholders will struggle to maintain their livelihood portfolio and agricultural productivity during extended periods of heat stress. These findings should motivate similar studies from other contexts, given that these results may be specific to the context studied here. These observations also provide explanation for related research on environmental migration in Uganda, where in researchers found that long periods of heat stress are associated with an increase in permanent out-migration (Call & Gray, under review). Taken together, these findings suggest that new livelihood strategies will be necessary if smallholders are to successfully adapt to climate change.

Conflict of interest statement

None.

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